On the Study of NEI Regime in SNR's: Emission Model and ROSAT PSPC Spectral Fitting Simulations

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Abstract. We developed and tested a Non-Equilibrium of Ionization (NEI) emission model to study the X-ray emission of supernova remnants (SNR's) with a parametric fitting approach. We present results of *ROSAT* PSPC spectral fitting simulations with our emission model. We found that, the confidence ranges of the plasma temperature tend to be larger with respect to fits with equilibrium of ionization models, the χ^2 function is characterized by local minima in the parameter space, and there is a strong dependence of the fit results on the initial value of the ionization time used in the minimization algorithm. We explain these findings in terms of the particular nature of the model. We conclude that, in typical cases of young and middle-aged SNR with a moderate ISM absorption, the local minima can be avoided by the χ^2 fitting spectra with 5000 counts or more. Finally, we briefly discuss how this limit affects the feasibility of spatially resolved spectral analysis of SNR's observed with the PSPC.

1. Introduction

In spite of the fact that Non-Equilibrium of Ionization (NEI) emission models begin to be widely used in fitting SNR's X-ray spectra (e.g. Vancura, Gorenstein & Hughes 1995, V95 hereafter, Hughes & Singh 1994, HS94 hereafter), a full understanding of our capability to constrain the model parameters which the spectra depend on is still lacking. Of course, this capability depends on the detector and on the available counting statistics.

We have investigated this capability for a NEI model which we are using to interpret *ROSAT* and ASCA spectra of SNR. In this paper, we restrict ourselves to simulations of *ROSAT PSPC* spectra. A similar work has been carried out by Maggio et al. (1994) for Collisional Ionization Equilibirum (CIE) models.

2. The model

To properly model the X-ray spectra from the observed regions of the SNR's, we have built a grid of NEI spectra with the electron temperature, T_e, and the ionization time $\tau = \int_0^{t_{now}} n\, dt$ as free parameters; $t = 0$ is the time when a small volume of plasma is struck by the blast wave. T_e and the density n stay constant during the ionization process and the emerging spectrum depends only on the instantaneous T_e and n. This assumption, also discussed by Hamilton & Sarazin (1984), represents one of the most realistic approaches to the problem of determining the plasma history using parametric fits to the data, and it is particularly suited in case of high spatially resolved observations to probe the temperature of small shock regions. It has already been adopted in the literature also by Hwang et al. (1993) and V95. Our calculation of the ionization populations is based on a modified fifth order Runge-Kutta method. The Raymond & Smith (1977+updates) code was used to synthesize the final spectrum that is saved in tabular form for usage with XSPEC.

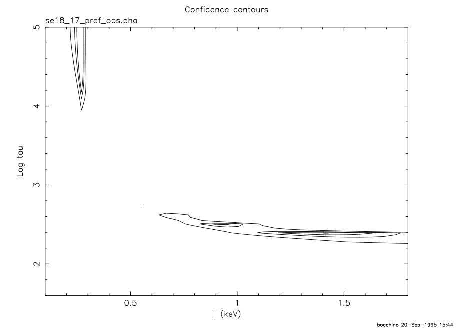

Fig. 1. Vela SNR χ^2 contours (see text).

Emission of plasma in low stages of ionization and high T could mimic a lower T and higher τ emission, especially if the spectrum is detected with moderate spectral resolution, e.g. with the *ROSAT* PSPC. This effect is showed in **Figure 1**, where we plotted χ^2 contours in the $T - \log\tau$ plane derived from the analysis of the PSPC spectrum of a region in the Vela SNR (Bocchino et al 1994), fitted with our emission model. In this case, traditional χ^2 minimization methods converge to one of the local minima depending on the initial choice of T and $\log\tau$, and the minimum χ^2 values are comparable. Model parameters can not be univocally derived from the fitting alone as in the case of equilibrium models. We stress that this is a model effect and not an effect of the algorithm or of the model gridding.

3. Simulations

We have performed four distinct sets of simulations using XSPEC V8.5. The **Set 1** address the topic of the statistical uncertainties of the best-fit parameters. We have adopted six different values ($\log\tau = 0, 1, 2, 3, 4$ and 5 in yr cm^{-3}), $\log\tau = 5$ corresponding to CIE conditions. For each $\log\tau$ value, we have generated 200 spectra with 2000 counts and 200 spectra with 5000 counts, including appropriate Poissonian noise. By choosing the input temperature, T_{inp}, and the input ionization time, $\log\tau_{inp}$, as initial guess of the fit free parameters ($T_0 = T_{inp}$ and $\log\tau_0 = \log\tau_{inp}$), we have explored the spread of the best-fit parameters around the input values.

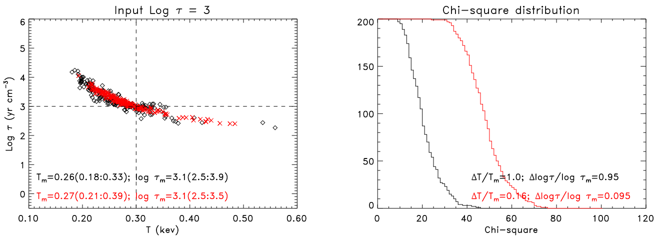

Fig. 2. (a) T and τ distributions of Set 1, $\tau_0 = \tau_{inp} = 10^3$. Black diamonds=2000 counts, Red crosses=5000 counts spectra. (b) χ^2 distribution of Set 3, $\tau_0 = 10^{2.5}$, $\tau_{inp} = 10$.

The simulations of **Sets 2, 3** and **4** have been done to try to understand if and under which conditions the fitting algorithm tends to be trapped in secondary χ^2 minima at T_{best} and $\log\tau_{best}$, far from the input values of the free parameters. We have made the following choices: $T_0 = T_{inp}$ and $N_{H_0} = N_{H_{inp}}$ for all sets, but we set $\log\tau_0 = 0.5$ in **Set 2**, $\log\tau_0 = 2.5$ in **Set 3** and $\log\tau_0 = 4.5$ in **Set 4**. These choices reflect the situations, common in the practice, in which we have no *a priori* knowledge about the plasma thermal history, and we try to infer it from the results of the fits. In interpreting the results, we adopted the 90% confidence level threshold ($\chi^2 \leq 38$ with 28 d.o.f.).

4. Results

The results of Set 1 simulations are: **a)** the fittings converge towards the input values of the parameters (Figure 2a). The elongated shape of the distributions is an intrinsic feature of the model (sec. 2).**b)** a plasma with $\log\tau_{inp} \geq 4$ can not be distinguished from a CIE plasma on the basis of the fitting results with the 2000 count spectrum. The ambiguity is removed by fitting spectra with 5000 counts.

In the case of Set 2, 3 and 4 simulations, we found that initial guess values far from the input ones make the algorithm to converge towards fake minima. In most of the cases, the false minima are recognized by an high χ^2 value but this is **NOT** always true: e.g. in the case of Set 3 (Figure 2b), $\log\tau_0 = 2.5$, $\log\tau_{inp} = 1$ 172 fits (86%) give acceptable χ^2 and totally wrong best fit values with 2000 counts. This problem is almost completely removed (only 10% of fake good fits) at 5000 counts. The same occurs also for 5 other combinations of τ_0 and τ_{inp}.

Table 1. A list of selected SNR's detected with the *ROSAT* PSPC. Name, counts and spatial resolution (SR) achieved by authors are showed.

Name	Counts	SR	References
IC443	20000	3pc	Asaoka et al 1994,A&A,284,573
G156.2+5.7	7695	none	Pfeffermann et al 1991,",246,L28
G18.95-1.1	498	none	Aschenbach et al 1991,",246,L32
3C400.2	4600	none	Saken et al 1995,ApJ,443,231
G326.3-1.8	9170	none	Kassim et al 1993,",419,753
Tycho	165000	none[1]	Vancura et al 1995,",441,680
G13.3-1.3	9000	none	Seward et al 1995,",in press
G296.1-0.7	11158	11 pc	Hwang et al 1995,",431,819
G296.8-0.3	100	none	Hwang et al 1995,",431,819
W44	10000	5 pc	Rho et al 1995,",430,757
Vela	20000	0.5 pc	Bocchino et al 1994,",437,209

[1] Assuming that counts are uniformly distributed in a thin ($\Delta R/R = 12$) shell, we estimate that 5000 counts could be collected in a region with size of 0.5 pc.

5. Discussion

Spectral analysis with NEI requires more counting statistics than with CIE models, not only because there is one more parameter (τ) but also because of similarity of spectra with different combinations of T and τ. Results with higher spectral resolution detectors like ASCA show that $\log\tau \sim 2-3$ is a typical value in SNR's (e.g. V95, HS94): these are typical cases in which 5000 counts are required to recognize fake minima in the χ^2 fitting results. On the basis of our results, to avoid secondary minima problems when studying young or middle-ages SNR's we suggest: **i)** to repeat fits with different initial values (especially τ), using any *a-priori* knowledge if available; and **ii)** to perform PSPC spectral fittings with NEI models of spectra with not less then **5000** counts. This limit has an impact on the study of SNR's by *ROSAT* observations: in **Table 1** we show that out of 11 listed cases, only 5 are possible candidates for spatially resolved spectral analysis, and only for two (Vela and Tycho) we can reach sub-parsec scale and therefore a great level of detail with more than 5000 counts.

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